LES Modeling of Aerosol and Drizzle Effects in Marine Stratocumulus

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LONG-TERM GOALS

The development and improvement of cloud microphysical and radiative parameterizations for use in cloud and numerical weather prediction models.

OBJECTIVES

Detailed study of marine stratocumulus cloud microphysical and radiative processes using a high-resolution large eddy simulation (LES) model with explicit microphysics. Better understanding of interactions between microphysical, radiative and boundary layer thermodynamical processes in order to improve prediction of drizzle, marine stratocumulus cloud base height and visibility.

Towards this goal, we investigate:

1) The dependence of drizzle on marine stratocumulus cloud microstructure
2) The effects of aerosol and moisture fluxes on cloud base height, drizzle, and visibility
3) Methods to characterize and formulate variability of cloud parameters for use in numerical forecast models

APPROACH

The research is based on a high-resolution LES model of marine boundary layer stratocumulus clouds with explicit formulation of aerosol and drop size-resolving microphysics. The LES simulations, as well as observations from ASTEX filed project were used to: 1) develop a drizzle parameterization for marine stratocumulus clouds, and 2) study the effects of aerosol and moisture fluxes on cloud base height and visibility. Measurements obtained by Millimeter Wave Cloud Radar (MMCR) have been used to study the variability of radar reflectivity in boundary layer stratocumulus and low altitude stratiform clouds.

WORK COMPLETED

The following tasks have been completed this year:

1. The development of a one-term drizzle parameterization for stratocumulus clouds in the range of drop concentration from 10 to 60 cm^{-3}.
2. Analysis of over 50 LES simulations investigating the response of cloud base height, drizzle, and visibility range to the strength of CCN and moisture sources.
3. Analysis of the variability of boundary layer stratocumulus and low altitude stratiform clouds based on radar data collected over two years of observations.

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RESULTS

1. The development of a drizzle parameterization for stratocumulus clouds

Using regression analysis and LES simulations, we derived a simple drizzle parameterization for boundary layer stratocumulus clouds. The parameterized expression for drizzle is a function of the following variables: N - total drop concentration, Q_c - cloud water content, and Q_r - precipitating water content. The simulated clouds have cloud thickness up to 300 m, cloud drop concentrations in the range 10-60 cm^{-3}, liquid water content up to 0.6 g/m^3, and drizzle rates up to 1 mm/day. The scatter plot in Fig. 1 shows that the parameterized drizzle rates are well correlated with the exact values (the correlation coefficient of 0.85 and the accuracy of the one-term parameterization is 32%).
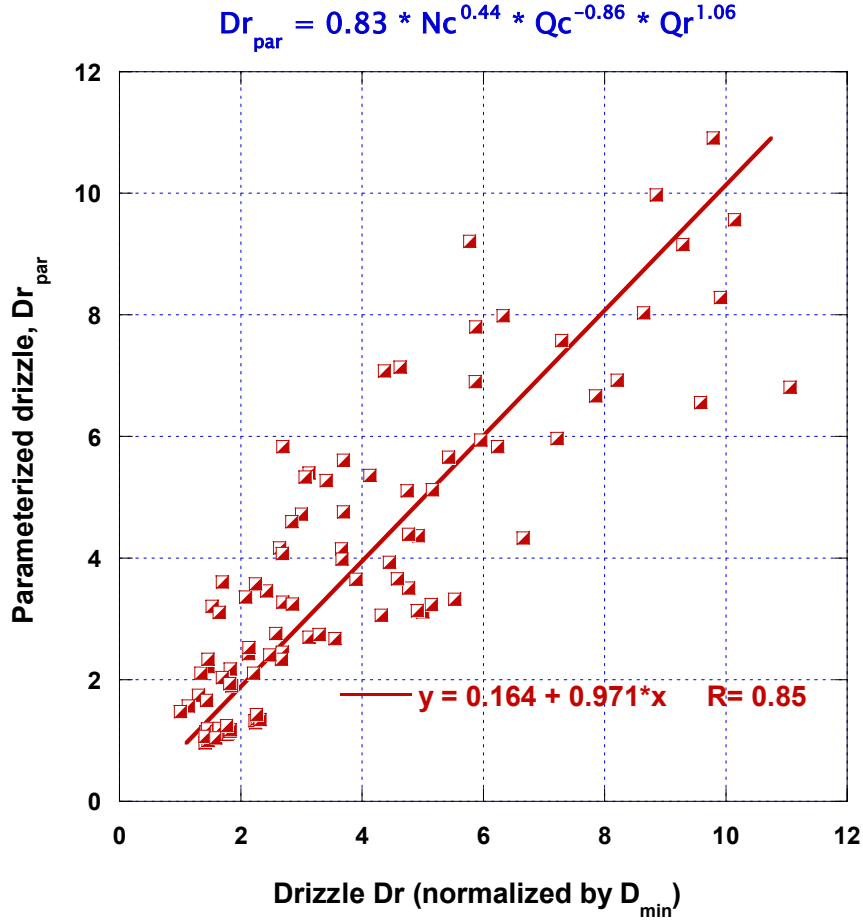
$$Dr_{par} = 0.83 * Nc^{0.44} * Qc^{-0.86} * Qr^{1.06}$$

Fig. 1: Parameterized vs exact drizzle rates (normalized by the minimum drizzle rate)

The one-term drizzle parameterization provides a reasonable mathematical fit to the data, however, it lacks physical basis. The accuracy of drizzle parameterization can be markedly increased if the functional dependency is sought in the two-term form:

$$DR_{par} = \Psi N^{\alpha} Q_c^{\beta} Q_r^{\gamma} + \Omega N^{\delta} Q_c^{\varepsilon}, \tag{1}$$

where $\Psi, \Omega, \alpha, \beta, \gamma, \delta, \varepsilon$, are regression coefficients. The two terms in parameterization (1) represent separate contributions from physical processes of accretion (coagulation between large and small

drops) and autoconversion (collisions between small drops). The work on the more advanced, physically based two-term parameterization (1) is currently underway.

2. *The effects of aerosol and moisture fluxes on boundary layer parameters*

The parameters of marine boundary layer are substantially affected by drizzle. Using observations and simulations with explicit microphysics LES model, we investigate how aerosols produced by surface winds (sea-salt) or by gas to particle conversion (background sulfates) and moisture flux produced by surface evaporation or by mesoscale horizontal divergence affect drizzle, cloud base height and visibility.

Over 50 experiments were conducted to simulate clouds in environments with CCN source term varying from 0 to 5×10^{-3} cm^{-3} s^{-1} and moisture source varying from 0 to 3×10^{-5} g m^{-3} s^{-1}.

Fig. 2 summarizes combined effects of CCN and moisture sources on selected cloud parameters. The general tendency shows increase in visibility with the increase of the CCN source, the result quite consistent with the physical notion of an increased colloidal stability in a more polluted environment. Larger CCN concentrations, in general, lead to higher values of cloud base height and a decrease in drizzle rate. On the contrary, the diminished supply of aerosols (due to cleaner air mass or weaker surface winds associated with smaller production of sea-salt aerosols) will increase drizzle, lower the cloud base height and reduce visibility in the boundary layer.

However, this general tendency is broken under certain combination of parameters. For instance, under conditions characterized by a large moisture source ($>2 \times 10^{-5}$ g m^{-3} s^{-1}) and low CCN replenishment rate ($<1.5 \times 10^{-3}$ cm^{-3} s^{-1}), the drizzle will remain stable due to counterbalance between the two competing physical mechanisms. The first is the increase in concentration of sea-salt aerosols that will increase the number of drizzle drop embryos leading to more drizzle. The second is lowering of in-cloud supersaturation following the increase in drop concentration; this eventually leads to decrease in drizzle rates. Stabilization of drizzle in this parameter range results in stabilization of cloud base height and visibility (Fig 2b and 2c).

When moisture source is less than 1.5×10^{-5} g m^{-3} s^{-1}, but more than 0.5×10^{-5} g m^{-3} s^{-1} the drizzle becomes a stronger function of CCN source and, consequently, there is a stronger dependence of cloud base height and visibility on CCN source. Clearly drizzle, cloud base height, and visibility are complex functions of CCN and moisture sources; however, they may also depend on the concentration of ambient sulfate aerosols which control supersaturation and drizzle.

In summary, the accurate prediction of cloud base height and visibility will require, in addition to thermodynamical characterization, also information on sources of sea-salt aerosols (hence, surface winds), as well as background sulfate aerosols. The latter affect cloud supersaturation and drizzle.
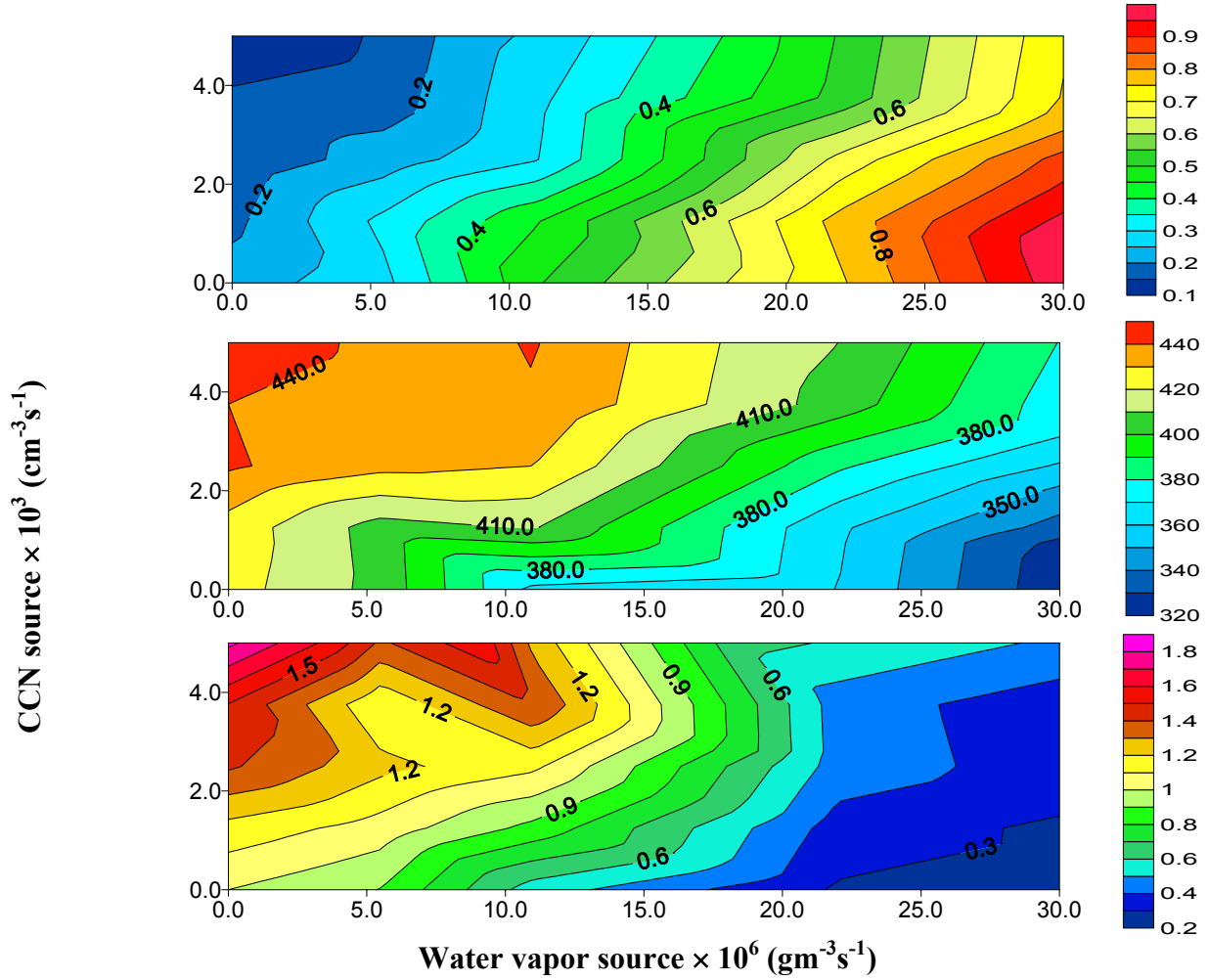
Fig. 2: Dependence of cloud parameters on CCN and water vapor source. Drizzle rate, mm/day, is shown in the top panel, cloud base height, meters, in the middle, and normalized visibility in the bottom panel. [Air mass with more CCN and less moisture produces higher clouds with less drizzle and a larger visibility]

3. The variability of boundary layer stratocumulus and low altitude stratiform clouds

The accurate formulation of cloud physics processes in a numerical weather prediction model requires adequate parameterization of sub-grid processes, in particular, the ability to characterize variability of cloud parameters. We analyzed 953 hours of overcast low stratiform cloud layers observed by a Millimeter Wave Cloud Radar (MMCR) in order to determine the probability distribution functions (PDFs) for low level stratiform and boundary layer clouds. Our analysis shows distinct differences between PDFs of precipitating and non-precipitating cloud systems, as well as between PDFs of two low stratiform cloud categories:

1. The total duration of all precipitating boundary layer clouds is only 1/3 that of non-precipitating boundary layer clouds. On the contrary, all precipitating low altitude clouds have about 25% greater total duration than non-precipitating.

2. Precipitating clouds typically exhibit much greater variability than non-precipitating clouds. This effect is especially pronounced in the low altitude stratiform category. Variability of low altitude clouds is greater (3 times for precipitating clouds) than of boundary layer clouds.

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3. For the boundary layer stratiform category, the PDFs of mean reflectivity are quite symmetrical for precipitating and non-precipitating cloud and in general can be well approximated by a two-parameter Gamma function.

4. PDFs of reflectivity for low altitude stratiform clouds demonstrate a different character. The non-precipitating category tends to be negatively skewed because of its shift towards greater reflectivity. PDFs in this category may be reasonably approximated with beta functions.

5. Most of the calculated PDFs can be reasonably approximated using well-known PDFs. This enables the calculation of a process rate over an NWP or GCM grid cell by integrating the rate expression over the PDF. This is equivalent to spatial integration of the local quantity over the grid itself. Using well-known PDFs is conducive to obtaining analytic expressions for a process rate integrated over the PDF. The PDFs of the boundary layer and low altitude categories differ substantially, as do precipitating and non-precipitating categories. This implies a need for the development of separate parameterizations to account for subgrid scale variability within these cloud types, as well as some method of "closure" to decide from the resolved model variables which of these PDFs to use.

6. Of the four categories studied, low altitude precipitating clouds would have the most pronounced effect on NWP forecast accuracy. The strong dependence of variability on radar reflectivity shown in Figure 3 allows the formulation of a PDF in terms of only one parameter — radar reflectivity — which may be related to the resolved model variables or predicted by future parameterizations.
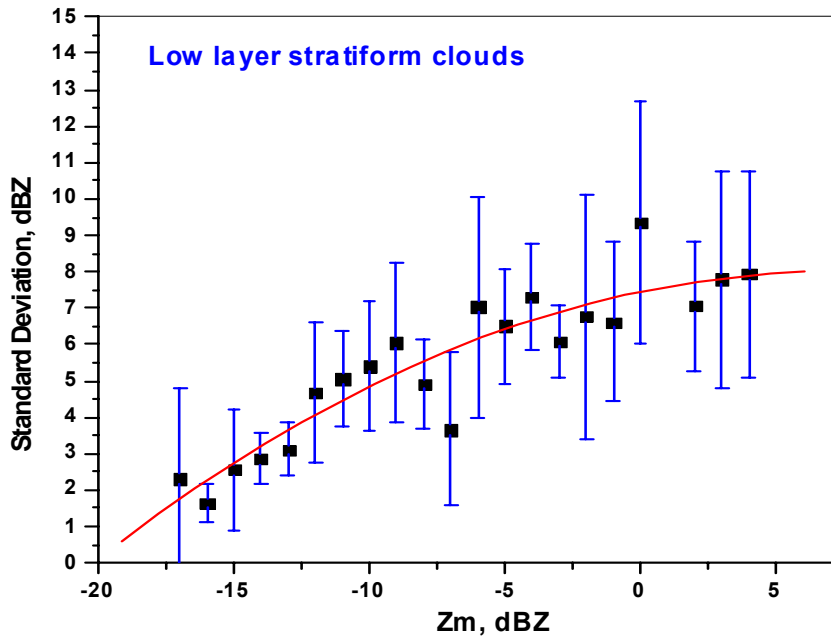

Fig. 3. Variability of radar reflectivity versus mean reflectivity for precipitating low altitude stratiform clouds [Note increase of variability at larger reflectivities, i.e., at stronger precipitating clouds].

IMPACT

The improved parameterization of the physical processes in marine stratocumulus clouds will lead to more accurate numerical weather predictions for Navy operations. In particular, we expect an

improved forecast of precipitating clouds, cloud base height, and visibility. The proposed approach for development of physical parameterizations using regression analysis of LES model data verified against observations is appropriate for other investigations.

TRANSITIONS

Our results have been reported at four scientific meetings, published in refereed journals and conference proceedings (10 papers) and, thus, are known to the scientific community.

RELATED PROJECTS

The study is aimed at development of physical parameterizations for cloud scale (LES) models. It is related to the ONR project "Improvement of the cloud physics formulation in the US Navy Coupled Ocean-Atmosphere Modeling Prediction System (COAMPS)" awarded to the University of Oklahoma in 2002. The latter goal is to develop and implement physical parameterizations into mesoscale prediction models in general, and COAMPS in particular.

PUBLICATIONS

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